Naval Surface Warfare Center

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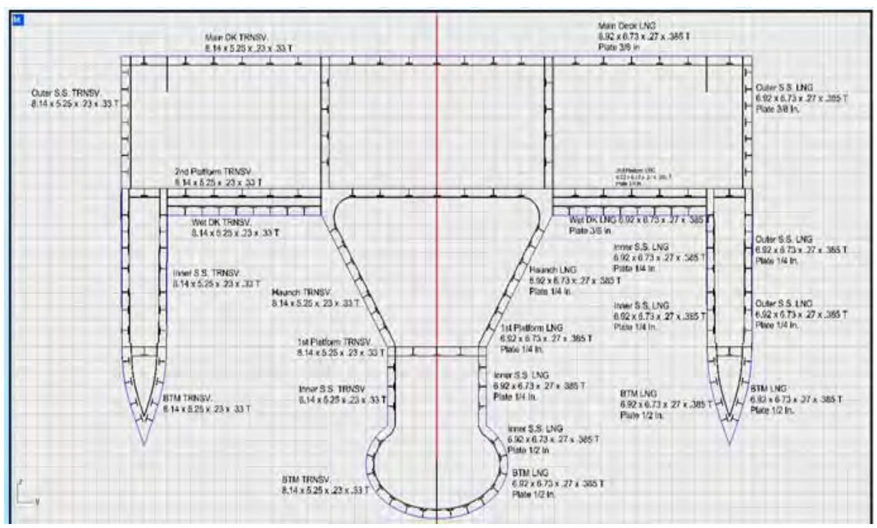
Center for Innovation in Ship Design

Technical Report

TriSWACH MATERIAL TRADE-OFF ANALYSIS

By

Alexandria Poole



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14. ABSTRACT
Shipbuilding is a naval art form that has been reformed and improved dramatically over the decades. Currently, a significant number of naval ships are constructed using specialized steels. This study was designed to conduct a material trade-off analysis between steel, titanium and aluminum for the design of a TriSWACH ship. The Design Program for Ship Structures (DPSS) and various material reports were used. Many different properties were factored into the analysis including: weight, usable space, plate thicknesses, total number of different stiffener types, estimated costs, producibility, and material physical properties. A run of the DPSS program was conducted for each material with three different frame spacings and three different stiffener spacings as well.

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Abstract

Shipbuilding is a naval art form that has been reformed and improved dramatically over the decades. Currently, a significant number of naval ships are constructed using specialized steels. This study was designed to conduct a material trade-off analysis between steel, titanium and aluminum for the design of a TriSWACH ship. The Design Program for Ship Structures (DPSS) and various material reports were used. Many different properties were factored into the analysis including: weight, usable space, plate thicknesses, total number of different stiffener types, estimated costs, producibility, and material physical properties. A run of the DPSS program was conducted for each material with three different frame spacings and three different stiffener spacings as well.

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Table of Contents

List of Tables

List of Figures

Acronyms

DPSS	Design Program for Ship Structures
GUI	Graphical User Interface
RSLS	Rapid Strategic Lift Ship
SHCP	Ship Hull Characteristics Program
SWATH	Small Waterplane Area Twin Hull
SWBS	Ship Work Breakdown Structure
TriSWACH	Trimaran Small Waterplane Area Center Hull

1. Introduction

Historically the most common material used for shipbuilding is various types of carbon steel. Steel is a very strong and low cost material that has proven over time to produce durable ships. It has historically been the go-to material for shipbuilding, but it has some disadvantages such as susceptibility to corrosion, need for constant maintenance and repairing, and high weight. Because of these negative properties it is necessary to explore other material options to potentially reduce costs, maintenance and total structural weight.

Titanium is a material that has appeared at the forefront of shipbuilding research. It has properties and advantages that make it attractive for ship structure, but its significant difference in cost, lack of compatibility with other materials, and requirement for specialized welding have inhibited its application to ship structure.

Aluminum is more commonly used in the shipbuilding industry due to its significant light weight. Weight is a major factor to be considered in shipbuilding when analyzing the impact to speed, stability, cargo payload and fuel efficiency. Steel's major drawback is its weight. Aluminum has the potential to provide a lighter ship, offering reduced displacement or increased payload capacity. Unfortunately, aluminum's stiffness and fatigue properties fall short when compared to that of titanium and steel thus mitigating its lightweight advantages for larger ships

The shipbuilding industry is continuously changing and improving in the methods, techniques, and materials used for ship construction. Many factors are analyzed when making decisions for materials and components in shipbuilding. Weight and strength of the material for the ship, the durability of the material throughout the ships lifespan and necessary maintenance are important factors. Other factors include the cost, the ease and feasibility of producing the particular ship, and the environmental friendliness of the process and ship.

1.1 Strength

Historically, steel is a very strong metal and can be alloyed to increase strength. The high strength steel that was used in this analysis has a yield strength of approximately 51,000 lb/in^2 and ultimate strength of 72,000 lb/in^2, as seen in Table 1.

Titanium has a higher ultimate strength than steel at 90,000 lb/in^2 allowing it to withstand higher forces and pressures. It also has a lower modulus of elasticity which makes it a more flexible material than steel and resistant to damage under high stress. Aluminum is not as strong as steel or titanium with a lower ultimate strength of 36,000 lb/ in^2 and yield strength of 26,000 lb/in^2. It also has a lower modulus of elasticity making it more flexible. Both titanium and aluminum have significantly lower elasticity's than steel. Ships experience a lot of pressure and forces acting against the hull due to waves and different sea states.

Table 1-Material Properties

Material	Yield Strength (lb/ in^2)	Ultimate Strength (lb/ in^2)	Modulus of Elasticity (lb/ in^2)	Density (lb/ in^3)
High Strength Steel HS	51,000	72,000	29,600,000	0.283
Titanium Ti-3Al-2.5V	70,000	90,000	15,000,000	0.160
Aluminum Al 5456-H116 P	26,000	36,000	10,000,000	0.094

1.2 Weight

Steel is a relatively heavy material in relation to titanium and aluminum. As shown in Table 1, titanium is approximately 43% less dense than steel. Aluminum is about 66% less dense than steel and about 31% less dense than titanium. Aluminum would ultimately produce a much lighter ship and is commonly used to produce small ships able to operate at higher speeds (Conner, 2010). A lighter ship is important to reach higher speeds or carry more payload.

1.3 Durability

Despite the high toughness and fire resistance of steel, one of the major drawbacks is its susceptibility to corrosion. The low cost of the material is counteracted by the constant maintenance needed. The corrosion of the hull form requires the use of coatings and paints to maintain the material and protect it from corrosion.

One of titanium's major advantages is its high resistance to corrosion, especially in sea water. This alone has potential to eliminate a lot of the hull maintenance expenses by eliminating the need for use of coatings and paints as is needed with steel. Titanium is more durable to the environmental effects which would result in a longer ship lifespan. In addition to the monetary savings, it also eliminates a lot of time and labor spent in maintenance and repairs. Titanium is also resistant to crevice, fatigue, and erosion corrosion (Mountford, 2002).

Aluminum is also resistant to corrosion, but only in environments where oxygen levels are high enough to maintain the self producing protective aluminum oxide layer. The material is slightly susceptible to crevice corrosion and pitting which can be reduced with the use of protective coatings, particularly on the underside of the ship. (Conner, 2010)

1.4 Cost/ Fabrication

Economic cost plays a significant role in material choices for the shipbuilding industry. Steel has been the preferred material in the shipbuilding industry because of its low cost. Aluminum is also a relatively low cost material. The major impediment to wider use of titanium as a hull structural material is its greater cost in relation to steel and aluminum. On average, titanium is about 89% more expensive than aluminum and about 91% more than steel. Using estimated structural weights from the DPSS designs and various pricing values obtained from multiple sources ([1]), material costs were estimated for the TriSWACH. Figure 1 displays average total costs per pound for each material. The figure shows that aluminum is marginally more costly than the equivalent steel structure while titanium is considerably more expensive.[1]

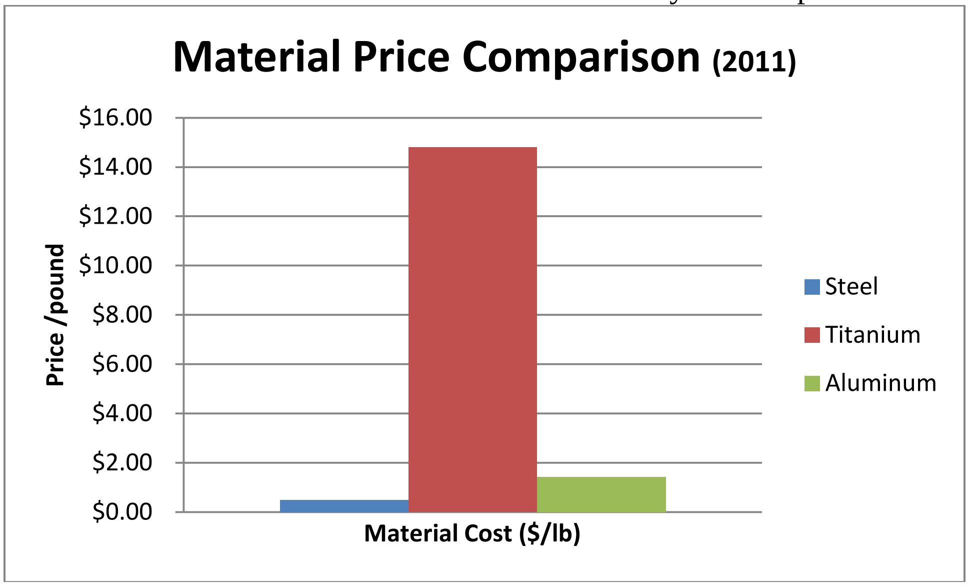

Figure 1- Material Analysis

There are other factors that have to be considered in addition to the material cost when evaluating the total ship cost. When dealing with steel ships, there is a significant maintenance cost associated with the repairs, paint and coatings necessary to control corrosion. Titanium does not require the constant maintenance of steel which reduces the through-life cost. In addition, titanium ships are expected to be more durable and have longer life spans than both steel and aluminum. (Mountford Jr. & Scaturro, 2010) Qualitatively, the high initial cost of titanium should be offset by a reduction in through-life maintenance costs compared to steel.

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[1] (Titanium PAge, 2011) (AMM The Metals Authority, 2011) (Aluminum Prices, 2011) (Free Titanium Charts, 2011) (Steel Prices, 2011)

1.5 Environmental Concerns

Another significant problem with the use of carbon steel in ships is the environmental hazards it presents during fabrication and construction as well as after the ship has been decommissioned and scrapped. Steel fabrication produces harmful gaseous fumes due to welding which requires numerous safety and precautionary measures to be used. Titanium and aluminum have little-to-no health concerns during the welding process and are more environmentally friendly materials. The use of certain inert gasses is required when welding titanium to maintain the quality of the welds. Titanium also retains significant scrap value at the end of the structure's useful life.

2. Analysis

In this material trade-off analysis, the Design Program for Ship Structures (DPSS) was used to determine certain design features of the TriSWACH ship in three different materials. High strength steel (HS), titanium (Ti-3Al-2.5V), and aluminum (Al 5456-H116P) structures were designed using common loads and design criteria. Three different frame spacing ranges and three different stiffener spacing ranges were evaluated for each material as shown in Table 2. This produced at total of 27 different designs. These designs were analyzed to compare their weight, producibility, plate thicknesses, total number of different stiffener types, and estimated cost. Due to DPSS design restrictions, some of the stiffener spacing had to be slightly modified as the frame spacing was increased. Certain segments could only handle certain sized stiffener spacing so these values were altered accordingly.

Table 2- Frame and Stiffener Combinations

Combinations to be Analyzed				
Frame Spacing [ft]		4	6	8
Stiffener Spacing Ranges [in]	12 to 18	**X**	**X**	**X**
	18 to 24	**X**	**X**	**X**
	24 to 30	**X**	**X**	**X**

As stated, a total of 27 different midship section designs were completed, 9 of each material type. The following figures are examples of typical midship section outputs; here the differences between titanium and steel can be seen. These two midship designs were not restricted in stiffener spacing range, but both have a frame spacing of 8 Ft. In general, the size differences of the longitudinal and transverse members can be seen.

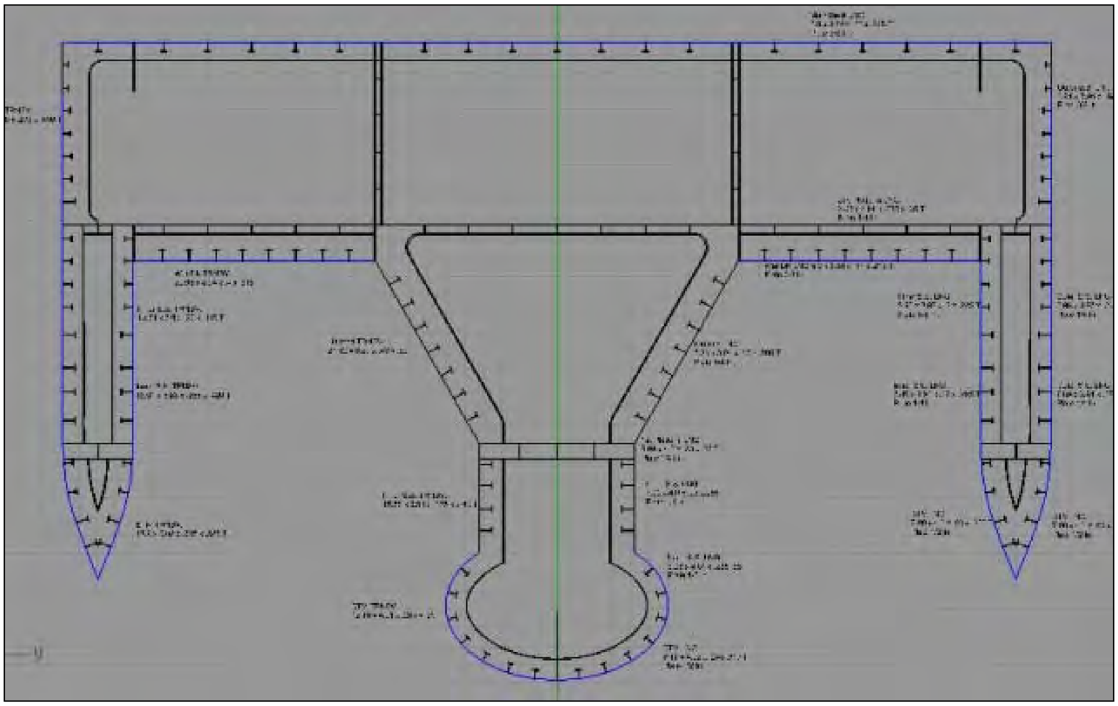

Figure 2:TriSWACH Steel Midship

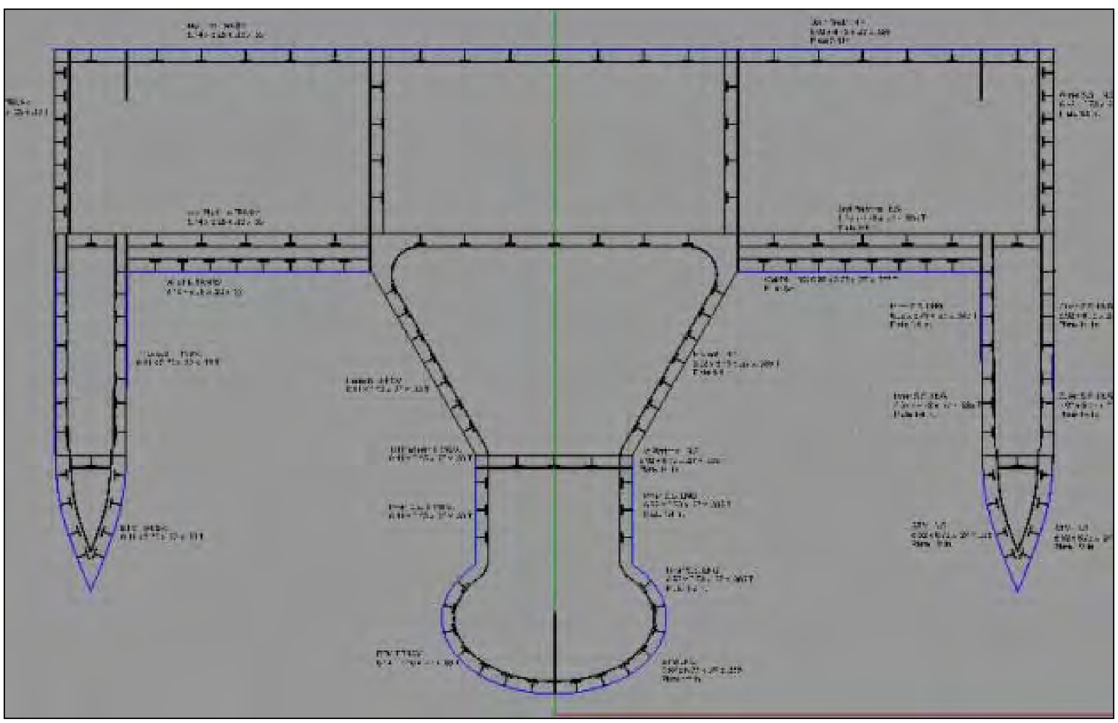

Figure 3:TriSWACH Titanium Midship

2.1 Weight

DPSS outputs a general hull structure Ship Work Breakdown Structure (SWBS) weight estimate based on the volume of material for frame, stiffener, and plating weights for each design. This weight summary is a normalized weight per length of the ship. Figure 4 displays this total weight per foot summary for steel, titanium, and aluminum at each of the different frame and stiffener range combinations shown in Table 2.

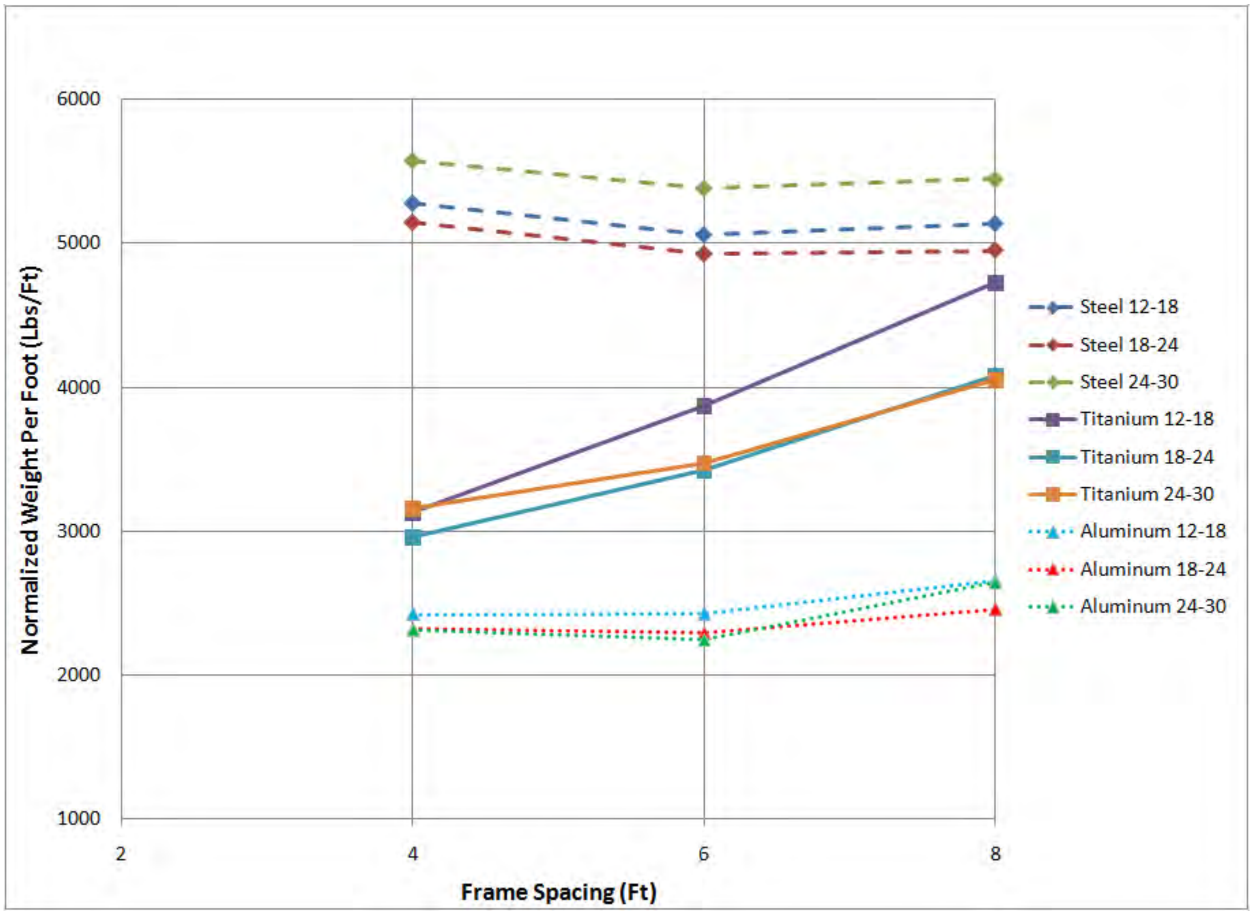

Figure 4- Weight per Foot Summary

The figure shows that there are significant differences in weight among the three materials. Steel, as expected, is significantly heavier per foot than titanium and aluminum. The lowest steel weight value is more than twice that of the lowest aluminum value and about 40% larger than the lowest titanium value. The lowest weight was aluminum with 6 ft frame spacing and stiffener spacing in the 18-24 inch range, although it was marginally lighter than the 4 ft frame case.

Table 3- Range of Weight per Foot Values

Range of Weight Per Foot Values		
Material	**Highest (Lbs/ Ft)**	**Lowest (Lbs/ Ft)**
Steel	5,578.3	4,925.7
Titanium	4,724.9	2,958.6
Aluminum	2,656	2,243.8

Some notable trends can be seen when examining the variations within the materials and differing stiffener and frame spacing. For steel, weights were lowest at the 18-24 inch stiffener spacing and greatest at the 24-30 inch spacing. However, there is only minor variation in weight for any of the steel designs. Within the three frame spacings for each stiffener range, weight per foot is lowest at the 6 ft frame spacing and highest for the 4 ft spacing.

Titanium weight per foot increases rapidly as the frame spacing increases. The values are higher for the 12-18 stiffener spacing, but there is little difference between the 18-24 and 24-30 spacing ranges. The lowest weight occurred at 4 ft frame spacing and a stiffener range of 18-24 inches. Aluminum frame spacing trends are similar to steel trends, but stiffener spacing variations are much smaller. The 12-18 inch stiffener range produced higher weight values than the other two ranges; the 18-24 and 24-30 inch ranges were extremely close in values although two of the lowest weights occurred in the 24-30 inch range. The lowest weight occurred at a 6 ft frame spacing and 24-30 stiffener range.

When considering the structural weight of a ship, it is important to recognize the different components that go into the value. Figure 5 displays a sample DPSS weight summary output.

```
                       SHIP WORK BREAKDOWN STRUCTURE (SWBS) WEIGHT SUMMARY
                       ---------------------------------------------------

SWBS                                               NORMALIZED                          VCG
GROUP        DESCRIPTION                         WEIGHT (LBS/FT)     PERCENT    (FT FROM BASELINE)
-----        -----------                         ---------------     -------    ------------------
 111     SHELL PLATING                               1306.0           41.37           16.74
 116     LONGITUDINAL SHELL FRAMES/STIFFENERS         196.0            6.21           16.15
 117     TRANSVERSE SHELL FRAMES/STIFFENERS           356.1           11.28           17.69
 121     LONGITUDINAL STRUCTURAL BULKHEADS            267.5            8.47           26.69    PAGE 18
 131     MAIN DECK STRUCTURE                         |445.9           14.12           35.07
 132     2ND DECK STRUCTURE                           473.2           14.99           25.23
 133     3RD DECK STRUCTURE                           112.4            3.56           13.39

 100     GENERAL HULL STRUCTURE (SUMMARY)            3157.1          100.00           21.40
```

Figure 5- Sample DPSS Weight Report Output

The weight summary takes into consideration the plate thicknesses, stiffener types, sizes, and the number of stiffeners needed for the shell, decks, and bulkheads. These elements influence one another to compensate for design requirements. DPSS allows the user to regulate or dictate certain values in the input, but only in a manner that doesn't violate the design. As stiffener spacing is increased (Figure 6), the plate thicknesses increase, particularly for the shell frame, as the design would require thicker plating with fewer stiffeners.

<table>
<tr><th colspan="2">Plate Thicknesses</th><th colspan="3">Shell Plating</th><th colspan="3">Deck Plating</th><th colspan="3">Bulkhead Plating</th></tr>
<tr><th>Stiffner Spacing [in]</th><th>Frame Spacing [Ft]</th><th>4</th><th>6</th><th>8</th><th>4</th><th>6</th><th>8</th><th>4</th><th>6</th><th>8</th></tr>
<tr><td rowspan="3">12-18</td><td>Steel</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td></tr>
<tr><td>Titanium</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td><td>0.25</td></tr>
<tr><td>Aluminum</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td></tr>
<tr><td rowspan="5">18-24</td><td rowspan="2">Steel</td><td>0.2813</td><td>0.2813</td><td>0.2813</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td></tr>
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<tr><td>Aluminum</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td><td>0.375</td></tr>
<tr><td rowspan="7">24-30</td><td rowspan="3">Steel</td><td>0.2813</td><td>0.2813</td><td>0.2813</td><td rowspan="3">0.25</td><td rowspan="3">0.25</td><td rowspan="3">0.25</td><td rowspan="3">0.25</td><td rowspan="3">0.25</td><td rowspan="3">0.25</td></tr>
<tr><td>0.4375</td><td>0.4375</td><td>0.4375</td></tr>
<tr><td>0.3438</td><td>0.3438</td><td>0.3438</td></tr>
<tr><td rowspan="2">Titanium</td><td>0.3125</td><td>0.3125</td><td rowspan="2">0.348</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td><td rowspan="2">0.25</td></tr>
<tr><td>0.3438</td><td>0.3438</td></tr>
<tr><td rowspan="2">Aluminum</td><td rowspan="2">0.375</td><td rowspan="2">0.375</td><td>0.375</td><td rowspan="2">0.375</td><td rowspan="2">0.375</td><td rowspan="2">0.375</td><td rowspan="2">0.375</td><td rowspan="2">0.375</td><td rowspan="2">0.375</td></tr>
<tr><td>0.5</td></tr>
</table>

Figure 6- Plate Thicknesses

The plate thicknesses provide information about the material itself. It can be seen that aluminum requires thicker plates in comparison to the other materials across the spectrum of combinations. Although a strong material in comparison to the other two materials, aluminum's lack of stiffness and weakness to fatigue results in thicker plating to withstand the pressures acting on the hull. Steel and titanium have consistently similar plate thicknesses.

2.2 Producibility

DPSS allows the user to regulate the type of stiffener for each segment of the structure within the allowable limits of the design. For the TriSWACH design, the shell segments were broken into four vertical zones and the stiffeners were held constant within each of these zones. The deck and bulkhead stiffeners were to all be the same within each zone. This limit was only placed on the longitudinal stiffeners of each zone.

Table 4- Designated Segments for Each Zone

Zone	Segments
Zone 1	1-4
Zone 2	5
Zone 3	6
Zone 4	7-11

An important factor to consider when designing and building ships is the number of different stiffener types that are needed in the structure. Ideally, from a cost and producibility perspective, the fewer number of different stiffener types needed the better, but this is not always the best structural design considering weight. There is a trade-off that allows the number of stiffener types to be reduced while maintaining light weight.

The specified stiffeners for the transverse framing are based on the design from DPSS. The charts below (Figure 7, Figure 8, & Figure 9) show the number of different stiffener types in the DPSS designs for each material and each frame/stiffener combination for the shell frame, deck frame, and total structure respectively.

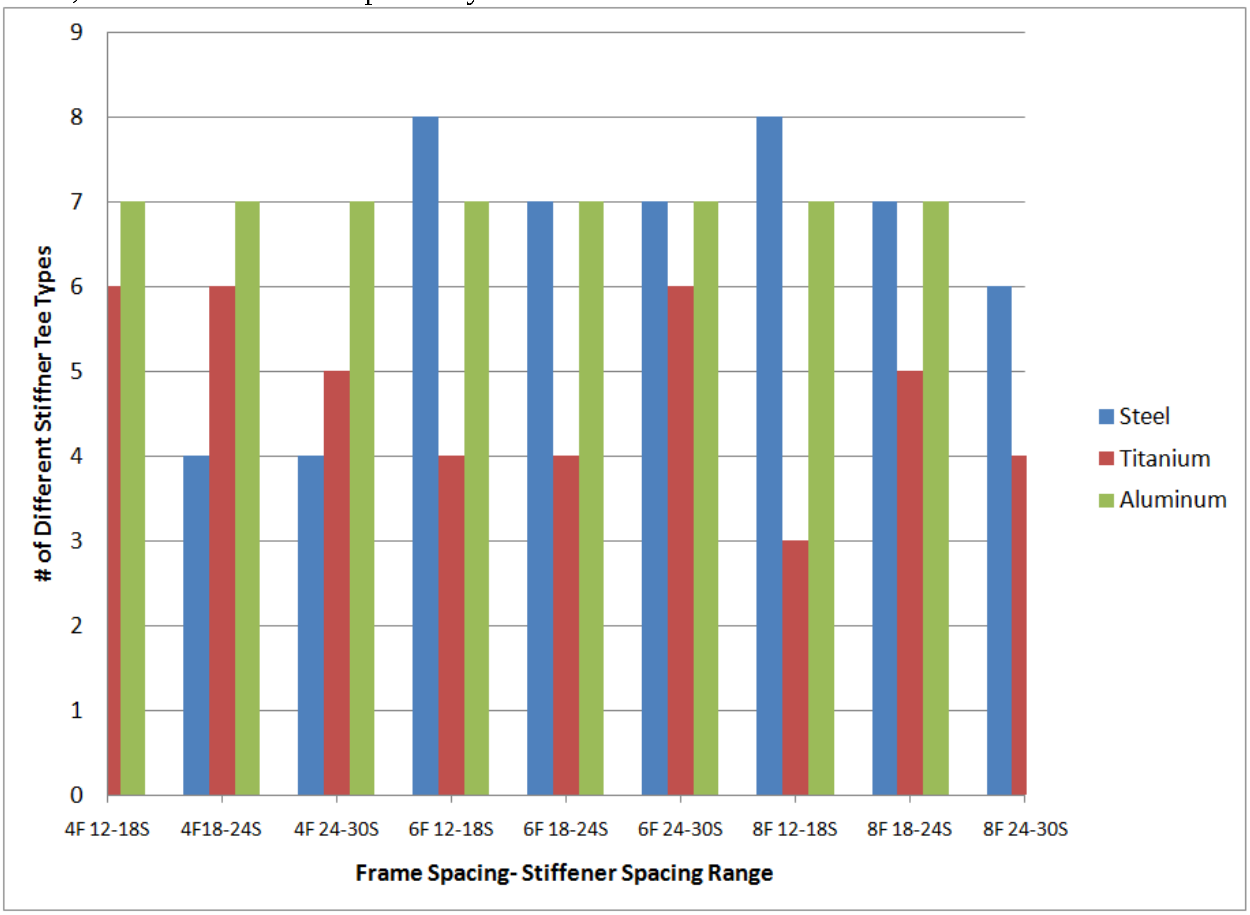

Figure 7- Number of Shell Frame Sizes

Figure 7 shows that with frame spacings of 6-8 ft, titanium requires fewer stiffener types for the shell. Steel requires the fewest number of stiffeners for the 4 ft frame spacing. The number of stiffeners remains quite constant for aluminum in all combinations while steel varies throughout. Steel has its lowest variation in types for the 4 ft frame spacing and is consistently high for the 6 and 8 ft frame spacing. Titanium varies throughout with its lowest value at an 8 ft frame spacing and highest in both 4 ft and 6 ft frame spacing.

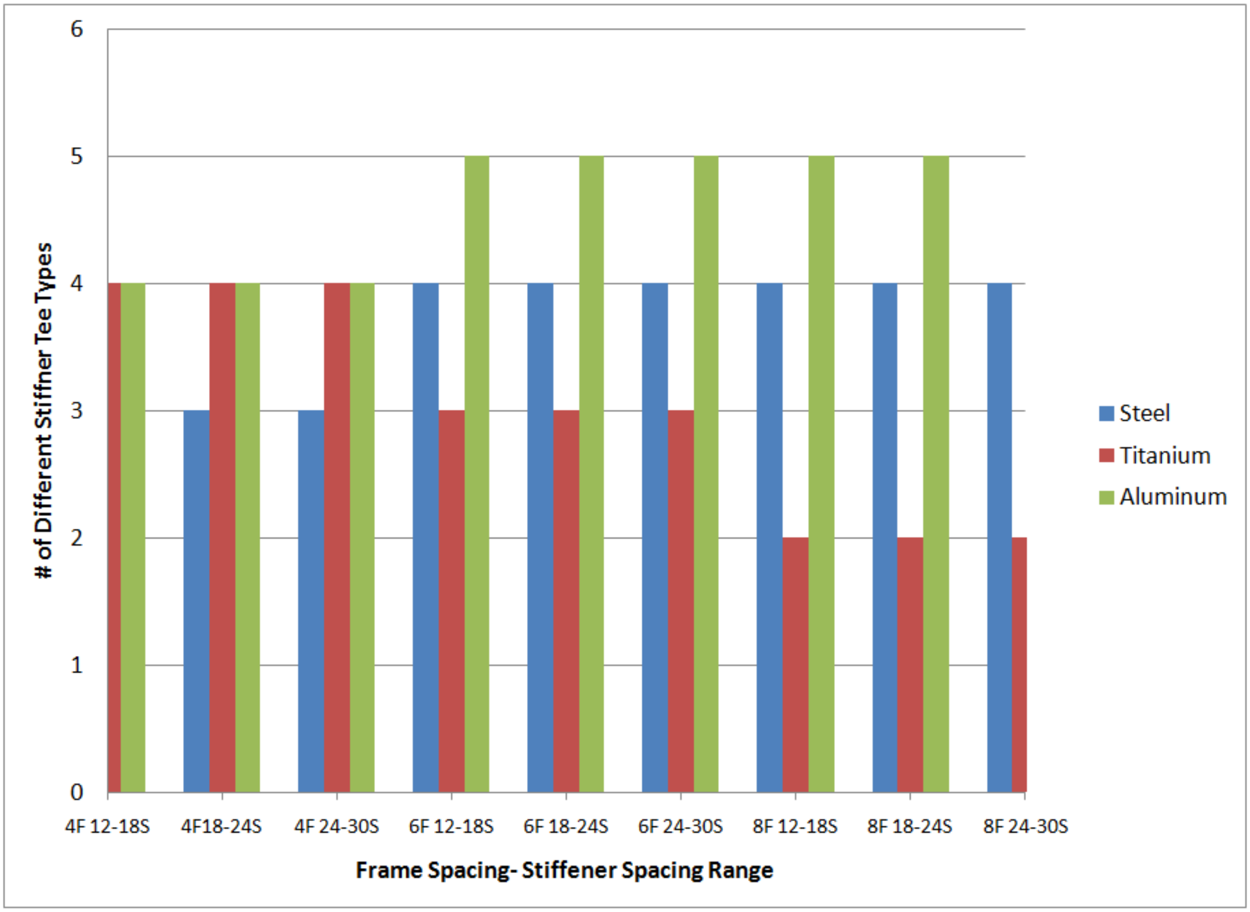

Figure 8- Number of Deck Frame Sizes

Figure 8 shows that fewer stiffener types are required for decks than for the shell. Titanium has a noticeable trend of decreasing numbers as the frame spacing increases. Aluminum is relatively constant across but increases as the frame spacing moves from 4 ft to 6 ft, making it generally higher than titanium. Steel follows the same trend as aluminum, but is at a lower value.

The total number of stiffener types in the structure, shown in Figure 9, presents a much clearer picture of the difference between materials. In all cases, aluminum requires more stiffeners than steel and titanium. As the frame spacing increases, the number of stiffener types for steel increases. Titanium is generally lower for 6 ft and 8 ft frame spacings than for 4 ft, but follows no distinct pattern throughout this range.

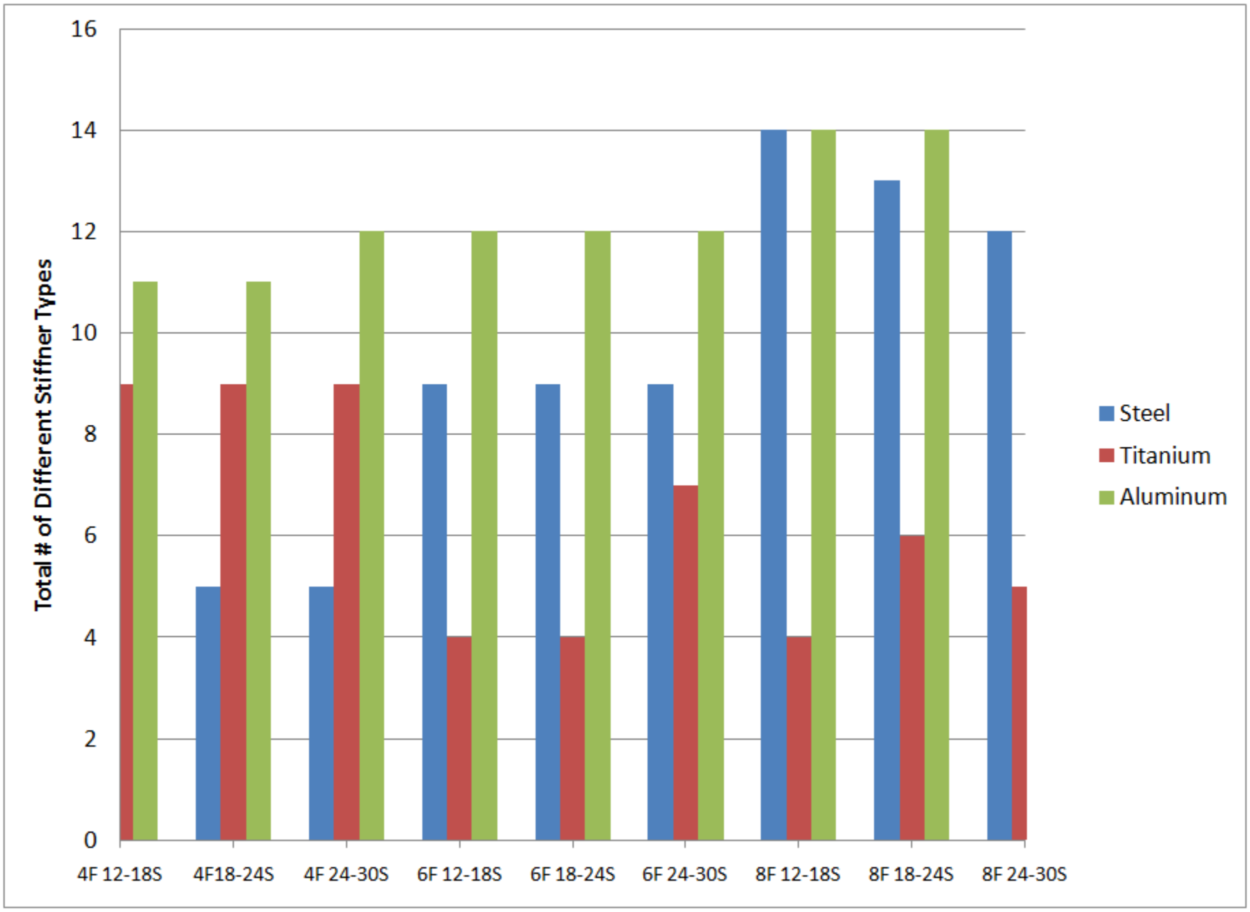

Figure 9- Number of Total Stiffeners

2.3 Usable Space

Another factor in deciding which stiffeners should be used is the amount of useable space available inboard of the shell stiffeners. This usable space may be needed for cargo, machinery or other uses on the ship. The TriSWACH was designed with a large centerhull and two small side hulls. With this design, the amount of usable space within these small sidehulls is problematic. The sidehulls are 46 inches wide before adding stiffeners and longitudinals. Using the transverse shell stiffener sizes defined by DPSS, the usable side hull space was calculated as shown in Figure 10.

There is clearly a significant difference in the usable space available for each of the different materials. Titanium provides the most available space in all combinations and aluminum provides the least amount of space. Overall the most space is available with 4 ft frame spacing and 18-24 inch stiffener spacing. Useable width for that combination with steel is approximately 46% (21.37 in), 59% (27.2 in) with titanium, and 30% (13.76 in) for aluminum.

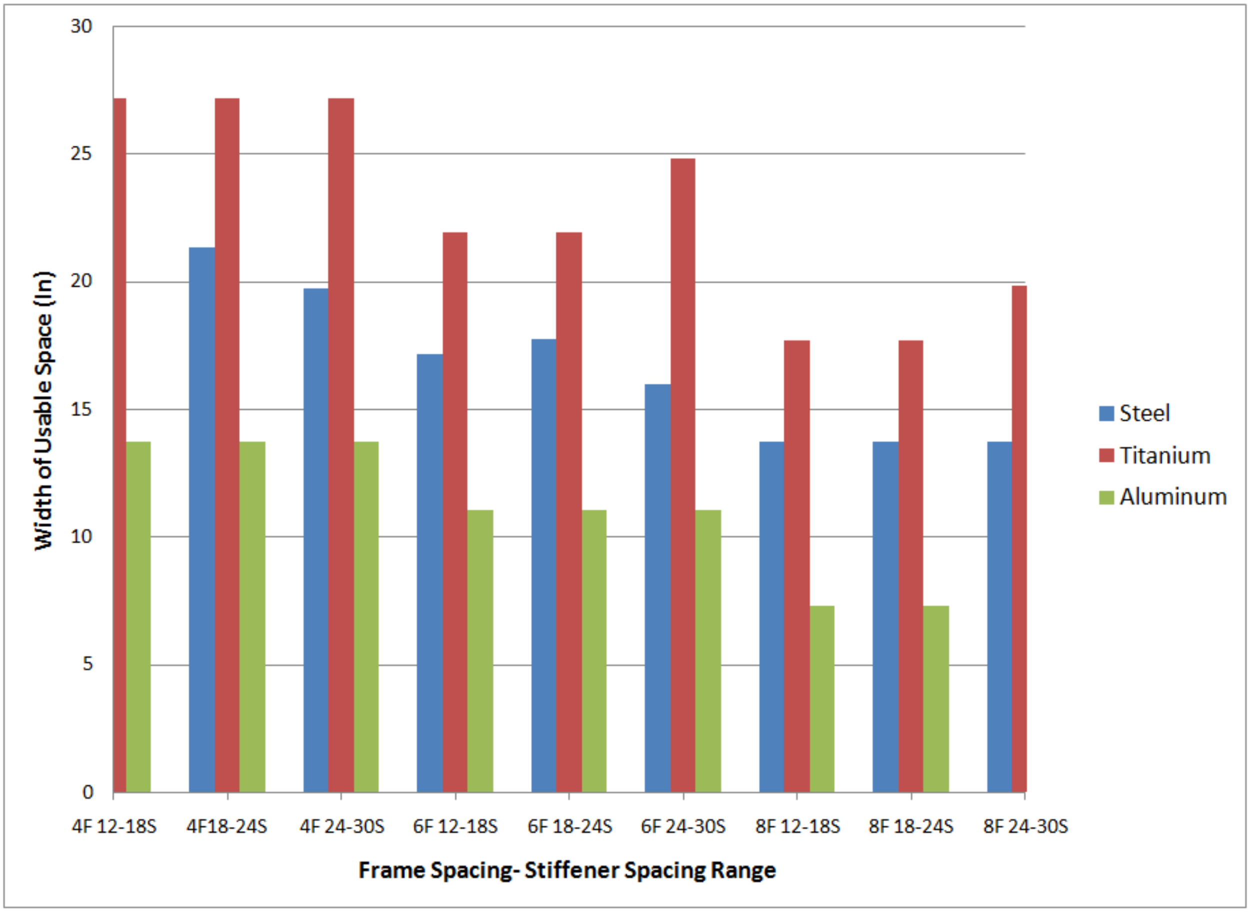

Figure 10- Sidehull Usable Space

3. Conclusion

Midship sections for a 1,000 LT TriSWACH hull were designed in high strength steel, titanium, and aluminum. The designs were produced with the Navy's Design Program for Ship Structures to be consistent with Navy material properties and design criteria. Variations in frame spacing and stiffener spacing were included in the designs. Analysis of the data identifies trends in weight per foot of midship section length, stiffener sizes, frame spacing, number of stiffeners in the structure, and cost for the three material choices.

Aluminum was found to be lightest weight. Although significantly lighter in weight, aluminum has poor stiffness properties that make it less desirable. This poor stiffness is reflected in the large number of stiffeners needed for the design and large size of them. It also requires thicker plating to withstand the pressure loads. Titanium is also a lightweight material in comparison to steel and has better strength properties than steel. The titanium designs required fewer stiffener types and relatively thin plating throughout. The major disadvantages are titanium’s higher material and construction cost.

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